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Electromagnetic Interference From Welding and Motors on Implantable Cardioverter-Defibrillators As Tested in the Electrically Hostile Work Site

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Objectives. **This study was designed to determine the susceptibility of an implanted cardioverter-defibrillator to electromagnetic interference in an electrically hostile work site environment, with the ultimate goal of allowing the patient to return to work.**

Background. **Normal operation of an implanted cardioverter-defibrillator depends on reliable sensing of the heart's electrical activity. Consequently, there is concern that external electromagnetic interference from external sources in the work place, especially welding equipment or motor-generator systems, may be sensed and produce inappropriate shocks or abnormal reed switch operation, temporarily suspending detection of ventricular tachycardia or ventricular fibrillation.**

Methods. **The effects of electromagnetic interference on the operation of one type of implantable cardioverter-defibrillator (Medtronic models 7217 and 7219) was measured by using internal event counter monitoring in 10 patients operating arc welders at up to 900 A or working near 200-hp motors and 1 patient close to a locomotive starter drawing up to 400 A.**

Results. **The electromagnetic interference produced two sources of potential interference on the sensing circuit or reed switch operation, respectively: 1) electrical fields with measured frequencies up to 50 MHz produced by the high currents during welding electrode activation, and 2) magnetic fields produced by the current in the welding electrode and cable. The defibrillator sensitivity was programmed to the highest (most sensitive) value: 0.15 mV (model 7219) or 0.3 mV (model 7217). The ventricular tachycardia and ventricular fibrillation therapies were temporarily turned off but the detection circuits left on.**

Conclusions. **None of the implanted defibrillators tested were affected by oversensing of the electric field as verified by telemetry from the detection circuits. The magnetic field from 225-A welding current produced a flux density of 1.2 G; this density was not adequate to close the reed switch, which requires ~10 G. Our testing at the work site revealed no electrical interference with this type of defibrillator. Patients were allowed to return to work. The following precautions should be observed by the patient: 1) maintain a minimal distance of 2 ft (61 cm) from the welding arc and cables or large motors, 2) do not exceed tested currents with the welding equipment, 3) wear insulated gloves while operating electrical equipment, 4) verify that electrical equipment is properly grounded, and 5) stop welding and leave the work area immediately if a therapy is delivered or a feeling of lightheadedness is experienced.**

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It is desirable that some patients with an implanted cardioverter-defibrillator be permitted to return to work despite the prevalence of electromagnetic interference at the work site. One major device manufacturer (Medtronic, Inc.) receives 15 to 25 telephone calls/month requesting information on external electromagnetic interference pertaining to arc welding, electric power and industrial sources with pacemakers and implantable cardioverter-defibrillators. These environments present a challenge to provide an ideal combination of arrhythmia protection and quality of life to the patient (1).

Certain industrial and medical work environments have long been recognized as exposing individuals to electromagnetic interference capable of interfering with normal pacemaker or defibrillator operation (2–6). Radiated electromagnetic fields contain both an electric and a magnetic field. The electrical sources consist of low frequencies from 0.1 to 10 Hz and the high frequencies from 10 kHz to 12 GHz (7). The most likely adverse effects of radiated electromagnetic interference are induction of electrical potentials within the defibrillator's sensing leads, which can cause inappropriate sensing resulting in uncalled for shocks, temporary suspension of arrhythmia detection, resetting to power-up conditions resulting in changed parameters or intermittent inhibition of pacing function.

The objectives of this study were 1) to evaluate susceptibility of a conventional implantable cardioverter-defibrillator to

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Table 1. Power Ratings of Electrical Equipment Capable of Producing Electromagnetic Interference Interaction on the Implantable Cardioverter-Defibrillator*

Equipment	Power Rating
Welders	
Lincoln arc	
TIG-300/300	AC or DC from 2 to 375 A
AC 2255	AC maximum 225 A
Weld-Pak	DC maximum 88 A
Portable	14 hp/130 A
Carbon arc	35 VDC/450 A
Submerged arc	30 VDC/900 A
Data Weld 650	30 VDC
2-simultaneous welding	375 A and 350 A
Forney	AC 180 A
Hobart Arc	
RC-500	28 VDC/250 A
MB-304	40 VDC/300 A
Miller AC/DC Gas Tungsten	30 V/310 A
Dialarc HF	(high frequency superimposed)
Millermatic	28 VDC/200 A
Apollo Arc	220 VAC/250 A
AC motors	200 hp, 460 VAC
	130 hp, 460 VAC/189 A
	20 hp, 220 VAC/40 A
Magnetek Transformers	75 KVA/506 VAC
Kohler model MV20 2 cylinder mower	20 hp, 25K Vignition†
EMD locomotive (GM)	Starter 200–400 A
Raymond Electric Forklift	6 hp, 24 VDC/43.8 A

*The study patients either used or were exposed to all equipment listed. †Magneto ignition as noted on motor faceplate. KVA = kilovolt amperes; VAC = volts alternating current; VDC = volts direct current.

electromagnetic interference in an electrically hostile work site environment, and 2) to measure the radiofrequency current spectrum radiated during exposure to typical direct current and alternating current welding and large industrial electric motors at the work site. The ultimate goal was to determine whether a patient with an implanted cardioverter-defibrillator can safely return to work in such an environment.

Methods

Patient testing. The study group comprised 11 patients, all male, with a mean age ± SD of 53 ± 11.7 years. Three patients had a model 7217 pacemaker cardioverter-defibrillator (Medtronic, Inc.) implanted in an abdominal location, and 8 had a model 7219 Jewel pacemaker cardioverter-defibrillator positioned in the prepectoral region. All patients had an implanted transvenous ventricular lead consisting of coaxial-wound conductors, a high voltage coil, plus a ring and active fixation helix for bipolar sensing implanted in the right ventricular apex.

Patients were tested in their work environment. Each was instructed to weld at a distance of ≤1-ft (30.5 cm) between the implanted defibrillator and weld arc or ≤1 foot from two-cylinder motors, large 200-hp 460-V alternating current industrial motors or an electric starter motor in a locomotive as described in Table 1. The ≤1-ft separation between the implanted defibrillator and the weld arc or two-cylinder, industrial or starter motors was maintained because of mechanical restrictions of machinery or electrical hazards and was believed to be an adequate distance that was both unlikely to jeopardize the patient's safety and considerably less than an arm's length or normal working distance from these sources. During the welding process the patient was exposed both to direct current and to alternating current, which can create severe electromagnetic interference. Each test was of >30-s duration to allow sustained exposure to the electromagnetic interference. The cables of the welding machines were either straight or coiled and not changed from their usual configuration. The magnetic flux, which indicates the magnitude of the magnetic fields produced by the welding equipment or motors, was measured with an F.W. Bell model 4048 gauss meter (frequency response direct current to 10 kHz) in the vicinity of the interference source.

Table 2. Implantable Cardioverter-Defibrillator Parameters Temporarily Reprogrammed During Testing at the Work Site

Parameter	Nominal	Test
Sensitivity	0.3 mV	0.15 mV (model 7219)
	0.3 mV	0.3 mV (model 7217)
VT NID	16	8
VF NID	18 of 24	12 of 16
VF detection	On/320 ms	On/320 ms
VT detection	On/400 ms	On/600 ms
VT/VF therapies	On	Off
Stability	On or off	Off
Onset	On or off	Off

NID = number of intervals to detect; VF = ventricular fibrillation; VT = ventricular tachycardia.

Each patient's test was coordinated with his primary care physician and permission from the physician, patient and work site management was obtained before proceeding with the tests.

Implantable cardioverter-defibrillator test protocol. The cardioverter-defibrillators implanted in this study provide noninvasive telemetered internal event counter information on episodes detected of ventricular tachycardia or ventricular fibrillation. Specific parameters in the defibrillator were temporarily reprogrammed (Table 2) to worst-case values to enhance the probability that detection of electromagnetic interference would produce inappropriate device operation. The sensitivity was reprogrammed to the most sensitive value available for each device model. Fibrillation and tachycardia detection intervals were set to nominal values with a minimal number of intervals to detect the interference. All ventricular tachycardia pacing or shock therapies and ventricular fibrillation shock therapies were temporarily disabled as a precaution in the event that the electromagnetic interference was sensed, thereby initiating a therapy. When feasible, the programmer head was retained over the implanted defibrillator to obtain continuous electrogram and marker channel telemetry. The

COUNTER DATA REPORT ---------- Page 1 of 2

Date Interrogated: Jun 09, 1995 11:51:19
Counters Last Cleared: Jun 09, 1995 11:48:06

TACHYCARDIA COUNTERS:		BRADYCARDIA PACING COUNTERS:	
VF:	1	Total Brady Pulses:	0
FVT:	0	Runs of > 3 Consecutive Pulses:	0
VT:	0		
ONSET CRITERION MET:	0	PREMATURE EVENT COUNTERS:	
		Isolated Premature Events:	0
		Runs of 2-4 Premature Beats:	0

VF THERAPY	Rx1	Rx2	Rx3	Rx4
INITIATED:	0	0	0	0
SUCCESSFUL:	0	0	0	0
ABORTED:	0	0	0	0
INEFFECTIVE:	0	0	0	0
CONVERTED TO VT:	0	0	0	0
CONVERTED TO FVT:	0	0	0	0
UNDETERMINED:	0	0	0	0

Medtronic 7219 SN RESET Rev 98700303 Jun 09, 1995 11:51

Figure 1. Counter data report telemetered by the model 7219D Jewel cardioverter-defibrillator to the programmer depicting the absence of detecting of any mimicked ventricular tachycardia (VT) or ventricular fibrillation (VF) due to exposure to electromagnetic interference. (The parameter 1 appears at the VF tachycardia counter only to illustrate detection of ventricular fibrillation; it is not indicative of this study because no episodes of ventricular tachycardia or ventricular fibrillation were detected during patient testing.) Brady = bradycardiac; FVT = fast ventricular tachycardia; R = registered events for each therapy.

model 7219 Jewel pacemaker cardioverter-defibrillator was reprogrammed to the "resume" parameter and the model 7217 pacemaker cardioverter-defibrillator to "cancel magnet," which reactivated the ventricular tachycardia and ventricular fibrillation detections that are temporarily suspended by the magnet in the programmer head.

The defibrillator was interrogated after the patient completed each specific work function to determine whether the ventricular tachycardia or ventricular fibrillation detection algorithms were satisfied by detection of electromagnetic interference. The stored comprehensive data were telemetered to the programmer and printed in a counter data report (Fig. 1). This report would identify any detected episode of ventricular tachycardia or ventricular fibrillation under the "Tachycardia Counters" column by the number 1 (or higher for multiple detections). All parameters were reprogrammed to their original value after completion of the test.

Results

Radiofrequency spectrum produced by welding. Electric welding produces a broad spectrum of energy (8). The radiofrequency current spectra, measured within a 1-MHz bandwidth on the cable connected to the operator-held welding electrode, are shown in Figure 2. The radiofrequency current amplitude decreases at high frequencies during direct current and alternating current arc welding. Near 2 MHz, spectral peaking is evident. The measured spectral levels are produced only during arc initiation when the machine is operated with spark "start only" in the direct current mode. When operating in the alternating current mode with spark "continuous," the measured spectral levels are produced continually.

Implantable defibrillator nondetection of electromagnetic interference. The electrogram and marker channel telemetered from the implanted defibrillator during patient testing

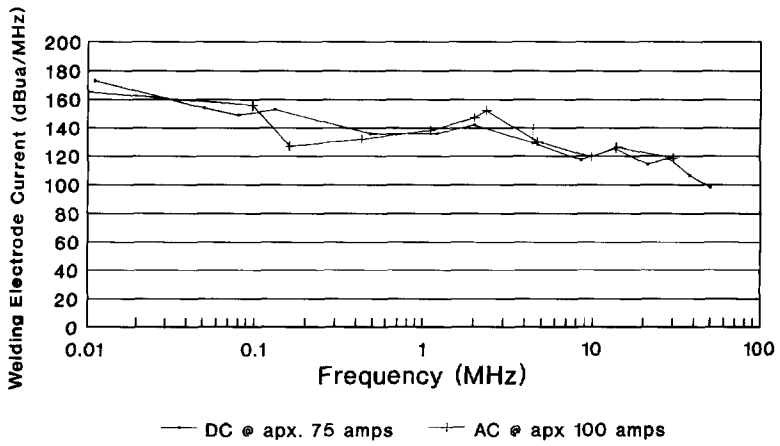

Figure 2. Radiofrequency current spectrum at the welding cable during welding at 75-A direct current (DC) and 100-A alternating current (AC) with a Lincoln Arc Welder model TIG 300/300. The radiofrequency current amplitude units utilize a standard normalized bandwidth of 1 MHz. apx = approximately; dBua = decibels $>1\mu A$.

Table 3. Magnetic Field Measurements*

Equipment	Test Current	Magnetic Flux Density (G)
Lincoln AC 2255	225 A	40, at cable surface; 1.2, at 2 ft from cable
Lincoln DC Weld Pak	88 A	44, at cable surface; 0.5, at 2 ft from cable
Mower, Kohler model MV20	Flywheel	2,530, at surface; 0.8, at 1 ft from surface

*The magnetic fields were measured directly at or 1 to 2 ft from the surface of the welding cable or flywheel containing a magnet in its magneto ignition system.

were recorded on the programmer only periodically because the electrical noise often prevented telemetry or ECG monitoring. The electromagnetic interference during welding or from the electric motors did not produce any extraneous artifacts on the normal sinus electrogram or extra detections on the marker channel due to inappropriate sensing. This condition of nondetection of electromagnetic interference prevailed even during exposure to welding with a high frequency voltage added to the welding current at an output of 310 A. At no time was any ventricular tachycardia or ventricular fibrillation counter activated by the radiated electromagnetic interference for any test conducted on any patient. There was no damage or reprogramming of any implanted defibrillator during the tests.

The amplitude of the magnetic fields produced for various types of welders and motors as measured with a gauss meter is shown in Table 3. The current in the return cable from the welding site to the welder causes a reduction of the magnetic field. The amount of cancellation depends on the spacing between cables. The defibrillators tested contained a magnetic reed switch that is closed by an ~10-G magnetic field. A strong magnetic field placed over the defibrillator temporarily suspends detection of ventricular tachycardia and ventricular fibrillation and the delivery of shock therapies. The field strength of the measured magnetic flux density decreased rapidly at 2 ft (61 cm) away from the source. The magnetic field from a 225-A welder was only 1.2 G at 2 ft from the cable, much less than that required to activate the reed switch. At no time during these tests was the magnetic field ≥2 ft from the welding cables of sufficient strength to close the defibrillator reed switch.

Discussion

Findings in this study indicate that electromagnetic interference generated by large welding machines and motors did not interfere with normal functional operation of the specific implantable defibrillators tested. No inappropriate sensing occurred and, ventricular tachycardia and ventricular fibrillation detection and pacemaker function were normal. All patients were able to return to work in what would seem to be an electrically hostile work site. There have been no subsequent reports of electromagnetic interference interaction with their implantable cardioverter-defibrillators.

The warning and precautions section of the technical manual for the defibrillators implanted in these patients states that exposure to electromagnetic interference may prevent detection of ventricular tachycardia or ventricular fibrillation, causing the device to sense inappropriately and as a result deliver an unneeded ventricular tachycardia or ventricular fibrillation shock therapy. There is a legitimate concern that patients are at risk if they do not keep away from sources of electromagnetic interference when the ventricular tachycardia and ventricular fibrillation detection function of their defibrillator is enabled. The concern that these devices will inappropriately sense the broad spectrum of radiofrequency energy measured up to 100 MHz during welding was addressed aggressively during this study. These data will be helpful in developing increased understanding of the characteristics of welding electromagnetic interference for future testing of implantable defibrillator compatibility.

Bipolar sensing characteristics. The defibrillators tested utilized standard bipolar sensing from a distal helix tip electrode to a small surface sensing ring spaced 1 cm apart. Closely spaced electrodes will reduce the sensing field for coupling electromagnetic interference to the sense amplifier. Previous studies (1,9,10) have demonstrated the noise discrimination superiority of bipolar sensing. Also, the electromagnetic interference effects from specified electric equipment are minimized with paired sensing electrodes spaced ≤1 cm apart (11). Standard bipolar sensing was a most effective mechanism for preventing transmission of inappropriate sensing of electromagnetic interference to the sense amplifier. This was clearly demonstrated by the absence of artifact interference, as denoted from the continuous monitoring of the patients' telemetered electrogram and marker channel during exposure to the source of electromagnetic interference. Filter circuits on the feedthroughs of the header connector and the sense amplifier bandwidth filter that rejects frequencies of <10 Hz and >60 Hz could also contribute to rejection of electromagnetic interference.

Sense amplifier operation. The self-adjusting sensitivity threshold amplifier in the tested defibrillators will automatically raise the sensing level to ~10 times the programmed sensitivity setting and return to the programmed value with an ~500-ms exponential decay time constant. This feature is designed to prevent the sensing of T waves at low sensing threshold levels. However, continuous artifacts sensed from electromagnetic interference could maintain the raised sensing level and reduce the amplifier sensitivity to the noisy electric environment but still maintain normal R wave sensing. This sense amplifier operation will contribute to maintaining pacemaker function in the defibrillator, providing backup bradycardia support during exposure to electromagnetic interference.

Magnetic field inhibition. Electromagnetic interference has been reported to deactivate a specific model of implantable cardioverter-defibrillator by closing its magnetic reed switch and rendering the patient without protection from ventricular

tachycardia or ventricular fibrillation (12). Patients with an implanted cardioverter-defibrillator have been counseled carefully to avoid close contact with devices such as arc welders, which emit a powerful magnetic field (13). The magnetic flux generated by a 225-A current flowing through the welding cable was measured to be 40 G at its surface; this level is capable of activating the reed switch should these cables be placed directly over the implanted defibrillator, as is possible when they are carried over a worker's shoulder on the side of the implanted defibrillator. At 2 ft from the cable surface, this same magnetic field decreased to 1.2 G, which was only a fraction of the level necessary to activate the reed switch. The field density required to close the defibrillator reed switch could actually be higher because of nonideal field alignment with the switch. The implanted defibrillator in a patient who is standing would normally be >2 ft away from electric cables lying on the floor and thus be far enough away to prevent reed switch activation by the magnetic fields emitted by these cables.

Study limitations. Testing was performed with a limited number of welders and motors in only 11 patients with an implanted defibrillator that utilized standard bipolar sensing electrodes spaced 1 cm apart and was produced by a single manufacturer. As there were no observed problems in the 11 patients, the upper 95% confidence limit for the failure rate of 0 is 24%. The effects of electromagnetic interference on implantable defibrillators may differ for 1) integrated bipolar sensing from a distal tip electrode to a large right ventricular shocking coil, 2) separation of the sensing electrodes by >1 cm (e.g., epicardial leads), or 3) electrodes with a larger surface area. Greater electrode separation and surface area will increase the sensing field and may increase the likelihood of sensing electromagnetic interference. Electrical characteristics of equipment can change either by failure of an arc welder or by a high voltage line affecting the amount of electromagnetic interference in the same work site. The model of the implantable defibrillator may change as a result of routine replacement procedure. It is advisable to reschedule another test for electromagnetic interference interaction should any of these differences be observed.

Conclusions. We conclude that certain implantable cardioverter-defibrillators are safe in general. However, it would be prudent to provide an extra margin of safety before the patient returns to an electrically hostile work site by 1) having a technical consultant from the device manufacturer conduct a comprehensive electromagnetic interference test with patients at their work site; 2) increasing the defibrillator sensitivity to 0.6 mV, programming the number of intervals to detect ventricular tachycardia to a minimum of 16 and programming the number of intervals to detect ventricular fibrillation to a minimum of 18; 3) determining the type of electrical equipment that the patient will be operating and assuring that appropriate electrical grounding is maintained in good condition; 4) ensuring that the patient's implantable defibrillator is ≥2 ft from the electrical source of the electromagnetic interference; 5) having patients wear gloves to avoid inadvertent contact with circuit electrical potentials; 6) advising patients to stop operating the electrical equipment if they experience a shock or lightheadedness and to immediately contact their primary physician.

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